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CHAPTER 15

POWER CABLE TESTING IN THE FIELD

James D. Medek

1. INTRODUCTION [15-1]

This chapter provides an overview of known methods for performing electrical tests in the field on shielded power cable systems. It is intended to help the reader select a test which is appropriate for a specific situation of interest. Field applied tests can be broadly divided into the following categories:

(1) Type 1 field tests are intended to detect defects in the insulation of a cable system in order to improve the service reliability after the defective part is removed and appropriate repairs performed. These tests are usually achieved by application of relatively elevated voltages across the insulation for prescribed duration.

(2) Type 2 field tests are intended to provide indications that the insulation system has deteriorated. Some of these tests will show the overall condition of a cable system and others will indicate the locations of discrete defects which may cause the sites of future service failures. Both varieties of such tests may be categorized as “pass/fail” or “go/no go” and are usually performed by means of moderately elevated voltages applied for relatively short duration, or by means of low voltages.

The following sections list various field test methods that are presently available for testing shielded, insulated power cable systems rated 5 kV through 500 kV. A complete tutorial or debate forum for one method versus another has not been attempted. A brief listing of “advantages” and “disadvantages” is included, but the users should avail themselves of the technical papers that are referenced, the material listed in the references, manufacturers’ literature, and recent research results to make decisions on whether to perform a test and which test method to use. In making such decisions, consideration should be given to the performance of the entire cable system, including joints, terminations, and associated equipment.

1.1 OVERVIEW

1.1.1 Summary of Direct Voltage Testing. DC testing [15-2] has been accepted for many years as the standard field method for performing high voltage tests on cable

insulation systems. Recent research has shown that dc testing tends to be blind to certain types of defects and that it can aggravate the deteriorated condition of some aged cables insulated with extruded dielectrics and affected with water trees. Whenever dc testing is performed, full consideration should be given to the fact that steady-state direct voltage creates within the insulation system an electrical field determined by the conductance of the insulation, whereas under service conditions, alternating voltage creates an electric field determined chiefly by the dielectric constant (or capacitance) of the insulation. Under ideal, homogeneously uniform insulation conditions, the mathematical formulas governing the steady-state stress distribution within the cable insulation are of the same form for dc and for ac, resulting in comparable relative values. However, should the insulation contain defects where either the conductivity or the dielectric constant assume values significantly different from those in the bulk of the insulation, the electric stress distribution obtained with direct voltage will no longer correspond to that obtained with alternating voltage. As conductivity is generally influenced by temperature to a greater extent than dielectric constant, the comparative electric stress distribution under dc and ac voltage application will be affected differently by changes in temperature or temperature distribution within the insulation. Furthermore, the failure mechanisms triggered by insulation defects vary from one type of defect to another. These failure mechanisms respond differently to the type of test voltage utilized, for instance, if the defect is a void where the mechanism of failure under service ac conditions is most likely to be triggered by partial discharge, application of direct voltage would not produce the high partial discharge repetition rate which exists with alternating voltage. Under these conditions, dc testing would not be useful. However, if the defect triggers failure by a thermal mechanism, dc testing may prove to be effective. For example, dc can detect presence of contaminants along a creepage interface.

Testing of extruded dielectric, service aged cables with dc at the presently recommended dc voltage levels can cause the cables to fail after they are returned to service [15-3]. The failures would not have occurred at that point in time if the cables had remained in service and not been tested with dc [15-4]. Furthermore, from the work of Bach [15-5], we know that even massive insulation defects in solid dielectric insulation cannot be detected with dc at the recommended voltage levels.

After engineering evaluation of the effectiveness of a test voltage and the risks to the cable system, high direct voltage may be considered appropriate for a particular application. If so, dc testing has the considerable advantage of being the simplest and most convenient to use. The value of the test for diagnostic purposes is limited when applied to extruded installations, but has been proven to yield excellent results on laminated insulation systems.

1.1.2 Summary of Alternative Test Methods. Alternating voltage tests at

alternating voltages are highly acceptable since the insulation is stressed in a similar way to normal operation and the test is similar to that used in the factory on new reels of cable.

A serious disadvantage of power frequency ac tests at elevated voltage levels was the requirement for heavy, bulky and expensive test transformers which may not be readily transportable to a field site. This problem has been mitigated through use of resonant (both series and parallel) test sets and compensated (gapped core) test transformers. They are designed to resonate with a cable at power frequency, the range of resonance being adjustable to a range of cable lengths through a moderate change of the excitation voltage frequency, or a pulse resonant system. Power frequency ac tests are ideally suited for Type 1 field tests, such as partial discharge location, and dissipation factor ($\tan \delta$) evaluation.

Some of the practical disadvantages of power frequency tests are reduced while retaining the basic advantages by the use of very low frequency (VLF 0.1 Hz) voltage or by the use of other time-varying voltages. Examples of these latter are the oscillating wave (OSW, Section 10) and the alternating-polarity dc-biased ac voltage (APDAC). When such variations of power frequency test sets are used for conducting Type 1 tests, it is necessary to establish the equivalence of the results obtained at various voltage levels and test duration with corresponding results obtained by testing at power frequency.

A major objection to Type 1 field tests is the concern that application of elevated voltages without any other accompanying diagnostic measurements may trigger failure mechanisms which will not show during the test but which may cause subsequent failures in service. The test voltages enumerated previously can be used not only to force cable systems to fail at the sites of defects, but also to provide a useful evaluation of the condition of the insulation system.

As cable system insulations age, their dielectric properties undergo characteristic changes. These can be used to perform various Type 2 (diagnostic) field tests. A brief overview of the known methods follows:

For a defective cable insulation, the dc leakage current versus voltage plot departs from linearity as the voltage is increased beyond some threshold value (tip-up curve), allowing a simple diagnostic test to be performed in the field.

Another set of tests consists of applying a moderately elevated direct voltage across the cable insulation, removing the voltage source, shorting the cable while monitoring the short-circuit current as a function of time (depolarization current test), or measuring the voltage build up as a function of time after the removal of the short, (return voltage test) [1.1].

The rate of depolarization current decay or the rate of return voltage build up can be used as indicators of the degree of insulation aging. Measurement of polarization index (ratio of insulation resistance after 10 minutes to resistance after one minute of a voltage application) can also be utilized as an insulation diagnostic test.

As a cable deteriorates, its dissipation factor ($\tan \delta$) versus voltage plots can assume a gradually higher rate of increase (tip-up) beyond some threshold voltage. This test can be conducted either by means of a power frequency voltage or by means of a VLF voltage.

Water treeing in extruded cables causes a slight rectification of the ac voltage impressed across their insulation, producing a very small dc component in the ac leakage current. The magnitude of this component has been shown to increase with the severity of treeing.

Another developing diagnostic test, propagation characteristics spectroscopy (PCS), monitors the changes in the wave propagation characteristics (attenuation versus frequency spectrum) of a cable by means of a low voltage pulse which can be applied while the cable is energized and in service. Experiments have shown that the attenuation spectrum changes characteristically as the insulation ages.

The Type 2 field tests previously described are intended to monitor the overall condition of a cable insulation system throughout its length. At least two additional diagnostic methods are intended to identify the location of discrete defects which may be the site of future service failures. Service-aged cables with water trees have been shown to produce partial discharge (PD) signals from the tips of their longest trees, when subjected to time-varying voltage in the range of 1 to 3 times service level. The exact identification and of these discharge sites is now possible by means of equipment capable of functioning even in high ambient noise environments. The severity of defects is assessed by the closeness of the PD inception voltage to service voltage. Partial discharge location in installed cables is usually performed by means of power frequency excitation voltage sources, but also has been shown to be possible by means of APDAC, impulse voltage or oscillatory voltage. A guide covering the use of this method using very low frequency voltage under development. Another diagnostic test, known as the DIACS method, identifies the location of discrete impedance discontinuities or anomalies in the cable insulation through low voltage reflectometry. Water trees are reported to act as discontinuities after the cable has been pre-conditioned for some length of time by means of unipolar high dc and impulse voltages. The ability of this method to assess the severity of anomalies and to identify defective joints has yet to be demonstrated.

1.2 Need For Testing

While medium and high voltage power cables are carefully tested by the manufacturer before shipment with alternating or direct voltage, some defects may not be detected or, more likely, damage during shipment, storage, or installation may occur. Additional testing of completed installations prior to being placed in service, including joints and terminations, may be conducted. Additionally, many users find that, with time, these cable systems degrade and service failures become troublesome. The desire to reduce or eliminate those failures may lead cable users to perform periodic tests after some time in service. As well, cable users need special diagnostic tests as an aid in determining the economic replacement interval for deteriorated cables.

AEIC G7-90 [15-6] states that "There are no field tests available that will provide an exact measurement of remaining service life in an operating cable system." Users may mix cable types on a system, so there is a need to base the test voltages and time on the circuit basic impulse level (BIL) rather than on the type and thickness of the insulation.

Research work has begun to show that certain types of field testing may lead to premature service failures of XLPE cables that exhibit water treeing when tested in a laboratory. This substantiates some field observations that led to the concern about field test methods and levels of voltage. Additional data is being compiled rapidly. The traditional method of factory testing the insulation of medium voltage cable has been to subject it to high alternating potential followed by direct potential. Because of the size and weight of conventional ac test equipment, many systems have been field tested with dc or no field testing has been performed. Experience with paper insulated, lead covered cable systems that have been tested in the field with dc for over 60 years has shown that testing with the recommended dc voltage does not seem to deteriorate sound insulation, or if it does, it is at a very slow rate of degradation.

The decision to employ maintenance testing must be evaluated by the individual user, taking into account the costs of a service failure, including intangibles, the costs of testing, and the possibility of damage to the system. As proven non-destructive diagnostic test methods become available, the users may want to consider replacing withstand type voltage tests with one or more of these methods.

CAUTION: Cables subjected to high voltage testing that are not grounded for sufficiently long periods of time following such tests can experience dangerous charge buildups as a consequence of the very long time constant associated with dielectric absorption currents. For this reason, the grounding procedures recommended in appropriate work rules should be followed.

2. DIRECT VOLTAGE TESTING

2.1 Introduction

The use of direct voltage has a historical precedent in the testing of laminated dielectric cable systems. Its application for testing extruded dielectric cable systems at high voltage is a matter of concern and debate. Reference [15-3] contains information relevant to these concerns.

This section presents the rationale for using dc testing, including the advantages and disadvantages and a brief description of the various dc field tests which can be conducted. These are generally divided into two broad categories, delineated by the test voltage level: low voltage dc testing (LVDC) covering voltages up to 5 kV and high voltage dc testing (HVDC) covering voltage levels above 5 kV.

Testing with a dc voltage source requires that only the dc conduction current be supplied rather than the capacitive charging current. This may greatly reduce the size and weight of the test equipment.

2.2 Performing LVDC Tests

Equipment for producing these voltages are typified by commercially available insulation resistance testers. Some have multi-voltage range capability.

Cable phases not under test should have their conductors grounded. Ends, both at test location and remote, should be protected from accidental contact by personnel, energized equipment and grounds.

Apply the prescribed test voltage for specified period of time. It may be advantageous to conduct the test with more than one voltage level and record readings of more than one time period.

Such test equipment provides measurements of the insulation resistance of the cable system as a function of time. Interpretation of the results, covered in greater detail in [15-2], IEEE 400.1, usually makes use of the change in resistance as testing progresses. A value of polarization index can be obtained by taking the ratio of the resistance after 10 minutes to the resistance after 1 minute.

ICEA provides minimum values of insulation resistance in its applicable publications.

2.3 Performing HVDC Tests

Equipment for producing these voltages are typified by rectification of an ac power supply. Output voltage is variable by adjusting the ac input voltage. Output current, i.e., current into the cable system under test, may be measured on the HVDC side or ratio transformation of the ac input. For the latter case, the test equipment leakage may mask the test current and the interpretation of results.

Apply the prescribed test voltage for the specified period of time. Reference [15-2] provides guidance for the selection of test voltage and time.

The following three general types of test can be conducted with this equipment:

2.3.1 DC Withstand Test. A voltage at a prescribed level is applied for a prescribed duration. The cable system is deemed to be acceptable if no breakdown occurs.

2.3.2 Leakage Current -- Time Tests. Total apparent leakage output current is recorded as a function of time at a prescribed voltage level. The variations of leakage current with time (rather than its absolute value) provide diagnostic information on the cable system.

2.3.3 Step - Voltage Test or Leakage Current Tip-up Tests.

The voltage is increased in small steps while the steady-state leakage current is recorded, until the maximum test voltage is reached or a pronounced nonlinear relationship between current and voltage is displayed. Such departures from linearity may denote a defective insulation system.

2.4 Summary of Advantages and Disadvantages

Some of the advantages and disadvantages of dc testing are listed below:

Advantages

- ◆ Relatively simple and light test equipment, in comparison to ac, and facilitates portability.
- ◆ Input power supply requirements readily available.
- ◆ Extensive history of successful testing of laminated dielectric cable systems and well established data base.

- ◆ Is effective when the failure mechanism is triggered by conduction or by thermal consideration.
- ◆ Purchase cost generally lower than that of non-dc test equipment for comparable kV output.

Disadvantages

- ◆ Is blind to certain types of defects, such as clean voids and cuts.
- ◆ May not replicate the stress distribution existing with power frequency ac voltage. The stress distribution is sensitive to temperature and temperature distribution.
- ◆ May cause undesirable space charge accumulation, especially at accessory cable insulation interfaces.
- ◆ May adversely affect future performance of water-tree-affected extruded dielectric cables.

3. POWER FREQUENCY TESTING

3.1 Introduction

As the name implies, these test methods are based on using alternating current at the operating frequency of the system as the test source.

These methods have the advantage, unique among all the test methods described in this chapter, of stressing the insulation comparably to normal operating conditions. It also replicates the most common method of factory test on new cables and accessories.

There is a practical disadvantage in that the cable system represents a large capacitive load, and in the past a bulky and expensive test generator was required if the cable system was to be stressed above normal operating levels. This size and bulk can be offset by the use of resonant and pulsed resonant test sources, which are described later.

A further advantage of power frequency testing is that it allows partial discharge and dissipation factor (tan delta) testing for diagnostic purposes. Some other test sources also permit these measurements, but give rise to some uncertainty in interpretation, since the measurements are then made at a frequency other than

the normal operating frequency.

The factory quality tests on new cable are almost invariably made at the power frequency on which the cable will operate in service.

It would therefore seem logical that all field testing should use the same type of test voltage. However, a conventional power frequency transformer required even for full reel tests in the factory is a large and expensive device. Since a power cable may be made up of multiple reels of cable spliced together in the field, an even larger test transformer would be required to supply the heavy reactive current drawn by the geometric capacitance of the cable system.

The size of the transformer can be substantially reduced by using the principle of resonance. If the effective capacitance of the cable is resonated with an inductor, the multiplying effect of the resonant circuit (its Q factor) will allow the design of a smaller test transformer. In the ideal case of a perfect resonance, the test transformer will only be required to supply energy to balance the true resistive loss in the inductor and cable system. A further and significant reduction in size and weight of the test voltage generator can be achieved by use of the pulsed resonant circuit.

3.2 Test Apparatus Requirements

The following requirements are common to all three types of line frequency, resonant testing systems:

The apparatus may be provided with an output voltmeter which responds to the crest of the test waveform. For convenience this may be calibrated in terms of the rms voltage of the output (i.e., as 0.707 times the crest voltage.)

The output waveform is sinusoidal and should contain minimum line frequency harmonics and noise. This is of particular importance if diagnostic measurements (partial discharge, power factor, etc.) are to be performed.

Suggested maximum values for total harmonic and noise are:

- ☐ For withstand tests $\pm 5\%$ of the output voltage crest.
- ☐ For diagnostic tests $\pm 1\%$ of the output voltage crest.

It should be noted that certain types of voltage regulators using inductive methods for regulation tend to produce large amounts of harmonic distortion.

Line filters to minimize noise introduced from the power line are recommended

for diagnostic measurements.

The test system should be equipped with a means of controlling the output voltage smoothly and linearly. The resolution of the voltage adjustment should be not more than one percent of the maximum output voltage.

For withstand tests, the detection and indication of breakdown of the point at which breakdown occurs is defined by the over-current protective device of the test system. For this reason it is desirable that a high speed and repeatable electronic circuit be used to operate the system circuit breaker and that the circuit breaker be as fast operating as practical. Disconnection of the cable from the test system should occur in less than two cycles of input frequency.

It is desirable that the output voltage be controlled by an automatic voltage regulator to maintain constant voltage for the duration of the test.

In resonant systems, it is convenient to have an automatic resonance control which operates initially to resonate the test system and cable system under test.

If the test system is to be used for diagnostic measurements, the internal partial discharge should be low -- less than 5 PC is normally acceptable.

3.3 Characteristics of Test Systems

The operating characteristics of a conventional test set are similar to a power transformer, although there are significant differences in the design of the source equipment.

Resonant systems operate differently than conventional transformers in that they have a specific tuning range for the capacitance of the cable under test. Capacitance outside this range cannot be energized. The minimum that can be energized can be reduced to zero, in the series resonant system, by using an auxiliary capacitor of appropriate rating in parallel with the test sample. The parallel resonant test system can be energized with no connected capacitance. The maximum value is independent of the current or thermal rating of the test system and cannot be exceeded. A typical tuning range is of the order of 20:1, maximum to minimum capacitance.

Both conventional and resonant test transformers provide an output which stresses the cable system under test identically to that under normal operations.

The output of a pulsed resonant test system consists of a power line frequency modulated at a low frequency, such as one Hz. The stress distribution in the cable system under test is therefore identical to that under normal operation. The

only difference is that the magnitude of the stress varies periodically. The duration of the test must therefore be extended so that the cable under test is subjected to the same volt-time exposure as with a constant amplitude line frequency test.

3.4 Test Procedures

3.4.1 Conventional Transformers. When the cable has been prepared and appropriate safety precautions taken, the test set is energized and the voltage increased at a slow, linear way until the specified test voltage is achieved. It is then held constant for the specified test period. At the conclusion of the test period, it is reduced to zero at the same rate as that used for raising the voltage.

3.4.2 Resonant Systems. Proceed as in 3.4.1 except that the voltage is first raised to approximately 5% of the specified test voltage, and the system tuned, either manually or automatically if the facility is available. The tuning may also require minor adjustment when specified voltage is achieved.

3.4.3 Testing with System Voltage (Medium Voltage). It has been the utility practice for field crews to reclose an overhead circuit after a visual patrol is made of the circuit. The visual patrol is important in order to verify that any damaged equipment has been removed, downed lines have been restored, and feeds from alternate circuits have been disconnected. Fusing used in these operations are normally the size and type that was originally found in the switch.

This practice has been carried over to the Underground Residential Distribution (URD) circuits by the same operating crews that switched the overhead system. URD circuits have been re-energized either by the overhead fuse connection or by the use of a separable connector (elbow). In some cases continual re-closing and sectionalizing have been used to isolate a failure. This practice should be used sparingly since it may be damaging to the underground system. Reclosing in this manner may cause high voltage transients to be generated, and hence subject the circuit to excessive current surges. Both of those conditions may reduce the life and reliability of the underground circuit.

Devices have been developed to eliminate the need to re-energize a faulted underground circuit. With the use of a standard operating tester, a high voltage rectifier, the correct adapters, and an ac system source, a test can be applied to the underground circuit that will indicate whether a circuit is suitable for re-energization. A voltmeter phasing tester, in common use for overhead testing, can be modified to test underground circuits with the application of a high voltage rectifier and proper adapters. The voltmeter indicates the amount of charging current that is on the circuit being tested. Since the underground cable is a good capacitor, an un-faulted circuit would give a high reading when the

tester is first connected to the circuit. As the capacitance charges, the reading on the voltmeter will decrease. If the reading fails to decrease, a faulted circuit is indicated.

When any of the above tests is complete, all parts of the circuit should be grounded and the system made secure.

The recommended rate-of-rise and rate-of-decrease of the test voltage is approximately 1 kV per second.

The duration of an acceptance test on a new cable system is normally 15 minutes at specified voltage. Maintenance tests may be 5 to 15 minutes. Any diagnostic tests (such as partial discharge) may be performed during this period. The voltage should be maintained at the specified value to within $\pm 1\%$

4. PARTIAL DISCHARGE TESTING

4.1 Introduction

Partial discharge measurement is an important method of assessing the quality of the insulation of power cable systems, particularly for extruded insulation materials.

This chapter considers partial discharge from two points of view: the measurement of all partial discharges occurring within the cable system and the location of individual partial discharge sites.

4.2 Measurement of Partial Discharge

Perhaps the most significant factory test made on the insulation of full reels of extruded cable is the partial discharge test. This is usually done at power frequency, but can also be carried out at very low frequency and at some voltage significantly higher than normal working voltage to ground. Experience has shown that this test is a very sensitive method of detecting small imperfections in the insulation such as voids or skips in the insulation shield layer.

It would therefore seem logical to repeat this test on installed cables to detect any damage done during the shipping or laying or any problems created by jointing and terminating the cable. Unfortunately this is a difficult measurement to perform in the field due to the presence of partial discharge signals. However, in spite of the difficulty, this test has been performed in the field where some special circumstances suggest it is worth the time and expense involved. Typically this may be when damage or faulty installation is suspected or the cable route requires it to be of the highest possible reliability.

Once the necessary steps are taken to reduce the noise level below the partial discharge level to be measured, the test can provide a great deal of useful diagnostic data. By observing the magnitude and phase of the partial discharge signals and how they vary with increasing and then decreasing test voltage, results will disclose information on the type and position of the defects and their probable effect on cable life.

Noise reduction methods necessary for field tests of partial discharge usually include the use of an independent test voltage source such as a motor-generator, power line and high voltage filters, shielding and sometimes the use of bridge detection circuits.

Partial discharges can also be detected at system voltage with special sensors connected to the splice or termination, using the frequency spectrum of the discharges.

In summary, if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.

5. VERY LOW FREQUENCY (VLF, < 1 HZ.) TESTING

5.1 Introduction

Medium and high voltage power cables are carefully tested by the manufacturer before shipment with ac and/or dc voltages to ensure conformance with published specifications and industry standards. During transport, installation, and backfilling, cables are vulnerable to external damage. Therefore, cables may be tested prior to placing them in service to locate any external mechanical damage and to ensure that jointing and terminating work has been satisfactory. Periodic testing of service-aged cables may also be performed with the desire to determine system degradation and to reduce or eliminate service failures. Very low frequency (VLF) testing describes a testing technique for field testing of service-aged systems with extruded cable insulations.

Very low frequency (VLF) testing methods can be categorized as withstand or diagnostic. In withstand testing, insulation defects are caused to break down (fault) at the time of testing. Faults are repaired and the insulation is retested until it passes the withstand test. The withstand test is considered a destructive test. Diagnostic testing allows the identification of the relative condition of degradation of a cable system and establishes, by comparison with figures of merit, if a cable system can or cannot continue operation. Diagnostic testing is

considered as non-destructive.

In extreme cases, when the cable system insulation is in an advanced condition of degradation, the diagnostic tests can aggravate the condition of the cable and cause of breakdown before the test can be terminated.

The VLF Withstand Test Methods for Cable Systems are:

- VLF Testing with Cosine -- Pulse Waveform
- VLF Testing with Sine Waveform
- VLF Testing with Square Wave with Programmable Slew Rate

The VLF Diagnostic Test Methods for Cable Systems are:

- VLF Dissipation Factor ($\tan \delta$) Measurement
- VLF Partial Discharge Measurement

Field testing techniques frequently employ a combination of diagnostic and withstand test methods. They are selected based on their ease of operation and cost/benefit ratio. The various VLF test methods described are in commercial use and are accepted as alternate test methods in international standards.

5.2 VLF Testing with Cosine-Pulse Waveform

5.2.1 Method. The VLF cable test set generates a 0.1 Hz bipolar pulse wave which changes polarity sinusoidal. Sinusoidal transitions in the power frequency range initiate a partial discharge at an insulation defect, which the 0.1 Hz pulse wave develops into a breakdown channel. Within minutes, a defect is detected and forced to become a failure. It can then be located with standard, readily available cable fault locating equipment. Cable systems can be tested in preventive maintenance programs or after a service failure. Identified faults can be repaired immediately and no new defects will be initiated during the testing process. When a cable system passes the VLF test, it can be returned to service.

5.2.2 Measurement and Equipment. A dc test set forms the high voltage source. A dc to ac converter changes the dc voltage to the very low frequency ac test signal. The converter consists of a high voltage choke and a rotating rectifier that changes the polarity of the cable system being tested every five seconds. This generates a 0.1 Hz bipolar wave. A resonance circuit, consisting of a high voltage choke and a capacitor in parallel with the cable capacitance, assures sinusoidal polarity changes in the power frequency range. The use of a resonance circuit to change cable voltage polarity preserves the energy stored in the cable system. Only leakage losses have to be resupplied to the cable system during the negative half of the cycle.

The 0.1 Hz test set is easily integrated in a standard cable fault-locating and cable-testing system by making use of available dc hipot sets. Stand-alone VLF systems should be supplemented by cable fault locating equipment.

The cable system to be tested is connected to the VLF test set. In five to six steps, the test voltage is regulated to the test voltage level of $3 V_0$ (V_0 is phase to ground voltage). The recommended testing time is 15 to 60 minutes. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the cable and test set are discharged and grounded. When a cable fails the test, the VLF test set is turned off to discharge the system. The fault can then be located with standard cable fault locating equipment.

5.2.3 Advantages

- The VLF test uses a 0.1 Hz pulse wave which changes polarity sinusoidal. The sinusoidal transitions in the power frequency range may initiate a partial discharge at a defect which the 0.1 Hz pulse wave may develop into a breakthrough channel.
- Due to sinusoidal transitions between the HV pulses, traveling waves are not generated.
- Due to continuous polarity changes, dangerous space charges cannot develop. Cables can be tested with an ac voltage up to three times the conductor to ground voltage with a device comparable in size, weight, and power requirements to a dc test set.
- The VLF test can be used on extruded as well as oil impregnated paper insulations.
- The VLF test with cosine-pulse wave form works best when eliminating a few singular defects from an otherwise good cable insulation. The VLF test is used to "fault" the cable defects without jeopardizing the cable system integrity.
- When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service.
- Disadvantages. When testing cables with extensive water tree damage or ionization of the insulation, VLF testing alone is often "not conclusive". Additional tests which measure the extent of insulation losses will be necessary.

- Present limitations are the maximum available test voltage of 54 kV.

5.3 VLF Testing With Sinusoidal Waveform

5.3.1 Method. The VLF test set generates sinusoidal changing waves which are less than 1 Hz. When the local field strength at a cable defect exceeds the dielectric strength of the insulation, partial discharge starts. The local field strength is a function of applied test voltage, defect geometry, and space charge. After initiation of partial discharge, the partial discharge channels develop into breakthrough channels within the recommended testing time. When a defect is forced to break through, it can then be located with standard, readily available fault locating equipment. Cable systems can be tested in preventative maintenance programs or after failure. Identified faults can be repaired immediately. When a cable passes the VLF test, it can be returned to service.

5.3.2 Measurement and Equipment. The VLF test set is connected to the cable or cable system to be tested. The test voltage is regulated to the test voltage level of $3 V_0$. The recommended testing time is 60 minutes or less that can be found in VLF testing guides. VLF sets have to have sufficient capacity to be able to supply and dissipate the total cable system charging energy. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the test set and cable system are discharged and grounded. When a cable fails the test, the VLF test is turned off to discharge the cable system and test set and the cable fault can then be located with standard cable fault locating equipment.

In addition to standard 0.1 Hz sinusoidal very low frequency test sets, which have been in use for many years for VLF testing of electrical machines, see ANSI-IEEE 433 [8-2], several variations are also available to meet specific cable system test requirements:

- (1) VLF, less than 0.1 Hz, high-voltage generator with programmable test voltage wave forms for cable systems with mixed insulation:
 - Sine wave test voltage.
 - Bipolar pulse wave with defined slew rate.
 - Regulated dc test voltage with positive and negative polarity.
 - Programmable step test for all voltage waveforms.
- (2) VLF, 0.1 Hz, high voltage generator with loss factor ($\tan \delta$) measurement capability.
- (3) Partial discharge free, VLF, 0.1 Hz high voltage generator for

partial discharge testing.

4) Partial discharge free, VLF, bi-polar pulse with defined slew rate, high voltage generator for partial discharge testing.

5.3.3 Advantages

- Cables are tested with an ac voltage up to three times the conductor to ground voltage. After initiation of a partial discharge, a breakthrough channel at a cable defect develops.
- Due to continuous polarity changes, dangerous space charges do not develop in the cable insulation.
- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.
- The VLF test can be used on extruded as well as paper type cable insulations. The VLF test with sinusoidal wave form works best when eliminating a few defects from an otherwise good cable insulation. The VLF test is used to "fault" the cable defects without jeopardizing the cable system integrity. When a cable passes the recommended 0.1 Hz VLF test, it can be returned to service.
- VLF test sets with 0.1 Hz loss factor measurement capability for diagnostically identifying cables with highly degraded cable insulations are available and can be used with a 0.1 Hz withstand test.

5.3.4 Disadvantages

- When testing cables with extensive water tree damage or ionization of the insulation, VLF withstand testing alone is often "not conclusive." Additional tests which measure the extent of insulation losses will be necessary.
- Limitations are the maximum available test voltage of 36 kV rms and the maximum capacitive load of approximately 3 μF at 0.1 Hz (30 μF at 0.01 Hz). The total charging energy of the cable has to be supplied and dissipated by the test in every electrical period. This limits the size of the cable system which can be tested. A long testing time must be seen as an inconvenience rather than a limitation.

5.4 Tan Delta Test With VLF Sinusoidal Waveform

5.4.1 Method. Bahder et al., first used dissipation factor ($\tan \delta$) measurements to monitor aging and deterioration of extruded dielectric cables. Bach, et al., reported a correlation between an increasing 0.1 Hz dissipation factor and a decreasing insulation break-down voltage level at power frequency. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of the loss factor with a 0.1 Hz sinusoidal waveform offers comparative assessment of the aging of PE, XLPE, and EPR type insulations. The test results permit differentiation between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz sinusoidal waveform can be used as a diagnostic test. Cables can be tested in preventative maintenance programs and returned to service after testing. The loss factor measurements at VLF can be used to justify cable replacement or cable rejuvenation expenditures.

5.4.2 Measurement and Equipment. A programmable, high voltage VLF, 0.1 Hz test generator with loss factor measurement capability is connected to the cable system under test. The loss factors of $\tan \delta$ at V_0 , $\tan \delta$ at $2 V_0$, and the differential loss factor $\Delta \tan \delta$ ($\tan \delta$ at $2 V_0$ minus $\tan \delta$ at V_0) are measured. The measured values are used as figures of merit to grade the condition of the cable insulation as good, defective, or highly deteriorated.

For example, XLPE insulation is tested at a 0.1 Hz test voltage of V_0 and the $\tan \delta > 2 \times 10^{-3}$, the service aged cables should be replaced. The test voltage should not be raised above V_0 in order to prevent an insulation breakdown. If for a 0.1 Hz test voltage of V_0 , and the $\tan \delta \gg 1.2 \times 10^{-3}$, the service aged cables should additionally be tested with VLF $3 \times V_0$ for 60 minutes. When cable passes this test, it can be returned to service.

If for a 0.1 Hz test voltage at V_0 and $2 V_0$, the loss factors are $1.2 \times 10^{-3} < \tan \delta < 2 \times 10^{-3}$ and the differential loss factor $\Delta \tan \delta < 0.6$, the cable should be returned to service but monitored semi-annually.

If for a 0.1 Hz test voltage at V_0 and $2 V_0$, the loss factors are $1.2 \times 10^{-3} < \tan \delta < 2 \times 10^{-3}$ and the $\Delta \tan \delta > 1.0$, the cable should be replaced.

It must be understood that, for different insulations, installations, and cable types, $\tan \delta$ figures of merit can vary significantly from the values listed above. The test gives the best results when comparing present measurements against established historical figures of merit for a particular cable.

5.4.3 Advantages

- This test is a diagnostic, non-destructive test. Cable systems are tested with an ac voltage equal to the conductor to ground voltage.
- Cable system insulation can be graded between good, defective, and highly deteriorated.
- Cable system insulation condition can be monitored over time and a cable system history developed. Cable replacement and cable rejuvenation priority and expenditures can be planned.
- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

5.4.4 Disadvantages

- For a 0.1 Hz VLF test set, the maximum available test voltage is 36 kV rms and the maximum capacitive load is approximately 3 μ F.
- The test becomes useful after historical comparative cable system data have been accumulated.

The suitability, practicality, and effectiveness of these testing methods for service aged power cables with extruded dielectric insulation will have to be determined based on several criteria:

It is known that dc testing of extruded dielectric insulated cables is not very useful. In fact, it may cause cables to fail after having been returned to service. At this time, VLF test techniques are effective alternates for testing of service aged power cables with extruded dielectric insulation.

6. DISSIPATION FACTOR TESTING

6.1 Introduction

Note: Some of this material is also included in Section 5 above, but is left here to aid in an understanding of this method.

Periodic testing of service-aged cables is practiced with the desire to determine system degradation and to reduce or eliminate service failures. Dissipation factor testing describes a diagnostic testing technique for field testing of service-aged shielded cable systems.

6.2 Dielectric Loss

Service-aged, shielded cable can be described by an equivalent circuit as shown in Fig. 14-1. The cable capacitance per unit length, C , is:

$$C = 7.354 \epsilon' \log_{10} (d_i/d_c) \quad (15.1)$$

Where ϵ' = dielectric constant of the insulation
 d_i = the diameter over the insulation
 d_c = the diameter under the insulation (over the conductor shield)

If the space between the coaxial conductors is filled with a conventional insulating material, the cable conductance per unit length, G , is:

$$G = 2 \pi k \epsilon_v f C \tan \delta \quad (15.2)$$

The quantity $\tan \delta$ is used to designate the lossyness of the insulating dielectric in an ac electric field. This is called loss factor or the tangent of the loss angle δ of the material. Typical values of ϵ_v and $\tan \delta$ are shown in Table 15-1.

For an applied voltage, V , the current through the loss-free dielectric is I_C and the current due to the lossyness of the material is I_G , see Fig. 15.2. The angle formed by the current, $I = I_C + I_G$ and the current I_C is δ . The angle formed by the current, $I = I_C + I_G$ and the voltage, V , is q and $\cos q$ is the power factor. I , I_C , I_G are phasor quantities.

6.3 Method

The $\tan \delta$ test is a diagnostic test that allows an evaluation of the cable insulation at operating voltage levels. The test is conducted at operating frequency or at the VLF frequency of 0.1 Hz. When the $\tan \delta$ measurement exceeds a historically established value for the particular insulation type, the cable is declared defective and will have to be scheduled for replacement. If the $\tan \delta$ measurements are below an historically established value for a particular insulation type, additional tests have to be performed to determine whether the cable insulation is defective.

Tests conducted on 1,500 miles of XLPE insulated cables have established a figure of merit for XLPE, $\tan \delta = 4 \times 10^{-3}$. If the cable's measured $\tan \delta > 4 \times 10^{-3}$, the cable insulation is contaminated by moisture (water trees). The cable may be returned to service, but should be scheduled for replacement as soon as possible. If the cable's measured $\tan \delta < 10^{-3}$, it is not possible to predict the integrity of the cable insulation. The cable insulation could have many small defects, in which case the cable may operate satisfactorily for many more years. The $\tan \delta$ should be monitored regularly, and upon further deterioration of the dissipation factor, proper action taken. However, the cable could have only a few isolated large defects, which could cause it to fail upon returning it to service or within days after it has been re-energized. Therefore, if the measured $\tan \delta < 4 \times 10^{-3}$, it is recommended that a VLF test at $3V_0$ be performed to identify the large defects, remove and repair them.

6.4 Measurement and Equipment

Bridge type circuits are used to measure cable capacitance and $\tan \delta$. The most common are a Schering bridge and transformer ratio arm bridge. Both test sets require an ac HV source and a loss-free capacitor standard. For balanced bridges, the dissipation factor and cable capacitance is:

$$\text{Schering Bridge } \tan \delta = 2 \pi f C_I R_I \quad (15.3)$$

$$C_X = C_N R_I / R_2 \quad (15.4)$$

Transformer Ratio
Arm Bridge

$$\tan \delta = 2 \pi f C_I R_I \quad (15.5)$$

$$C_X = C_N W_I / W_2 \quad (15.6)$$

6.5 Advantages

- Tan δ measurements are diagnostic tests which permit assessment of the state of aging or damage of the cable insulation.
- Cables are tested with an ac voltage at operating voltage levels.
-
- The tests are performed at operating or at VLF frequencies.

- The $\tan \delta$ test can be used on plastic and rubber as well as on fluid impregnated paper type insulations.
- When a cable fails the $\tan \delta$ test, it can still be returned to service until repair or replacement has been scheduled.
- Monitoring of the $\tan \delta$ will establish a cable history and a deterioration will be noticed.

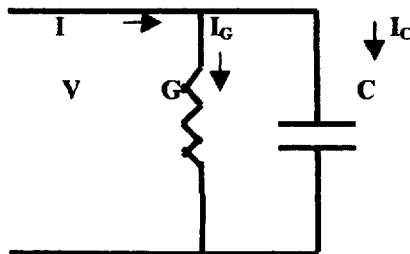
6.6 Disadvantages

- When a cable passes the $\tan \delta$ test, it is not possible to declare the cable insulation sound.
- A VLF or breakdown test will have to be performed to identify any large defects in the cable system insulation.

Table 15.1
Typical Values of Dissipation Factor

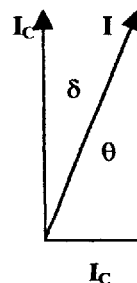
Type of Insulation	ϵ_v	$10^{-3} \times \tan \delta$
Impregnated paper	3.5	2.3
Impregnated PPP	2.7	0.7
XLPE	2.3	0.1
TR-XLPE	2.3	0.2
HDPE	2.3	0.1
EPR	2.8 to 3.5	3.5

Figure 15-1



Equivalent circuit of a lossy portion of a power cable.

Figure 15-2



Phasor diagram for lossy dielectric

6.7 Dissipation Factor With VLF Sinusoidal Wave Form

6.7.1 Method. Bach, et al., reported that loss factor ($\tan \delta$) measurements at VLF (0.1 Hz sinusoidal) can be used to monitor aging and deterioration of extruded dielectric cables. The 0.1 Hz loss factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of loss factor with 0.1 Hz sinusoidal wave form offers comparative assessment of the aging condition of PE, XLPE, and EPR type insulations. The test results permit differentiating between new, defective, and highly degraded cable insulations. The loss factor with a 0.1 Hz with sinusoidal wave form is a diagnostic test. Cables systems can be tested in preventative maintenance programs and returned to service after testing. The loss factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

6.7.2 Measurement Equipment. A programmable high voltage VLF test generator with loss factor measurement capability is connected to the cable under test. If for a test voltage of V_0 the $\tan \delta > 4 \times 10^{-3}$, the service aged cables should eventually be replaced. The test voltage should not be raised above V_0 in order to prevent insulation breakdown. If for test voltage of V_0 the $\tan \delta \ll$ than 4×10^{-3} , the service aged cables should additionally tested with VLF at $3 V_0$ for 60 minutes. When the cables passes this test, it can be returned to service without reservation. Loss factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

6.7.3 Advantages

- ◆ The test is a non-destructive, diagnostic test.
- ◆ Cables are tested with an ac voltage equal to the phase-to-ground voltage at which they operate.
- ◆ Cable system insulation can be graded as excellent, defective, or highly deteriorated.
- ◆ Cable system insulations can be monitored and history developed. Cable replacement and rejuvenation priority can be planned.
- ◆ Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

6.8.4 Disadvantages

- ◆ The maximum available test voltage is 36 kV rms and the maximum capacitive load is about 3 μ F.
- ◆ The test works best after comparative cable system data have been developed.

7. OSCILLATING WAVE TESTING

7.1 Introduction

Oscillating wave testing was selected by a CIGRE task force “alternative tests after laying” as an acceptable compromise using the following criteria:

- The ability to detect defects in the insulation that will be detrimental to the cable system under service conditions, without creating new defects or causing any aging.
- The degree of conformity between the results of tests and the results of 50 or 60 Hz tests.
- The complexity of the testing method
- The commercial availability and costs of the testing equipment.

The purpose of the Oscillating Wave (OSW) testing method is to detect defects that may cause failures during service life without creating new defects that may threaten the life of the cable system.

Although OSW testing does not have a wide reputation with respect to cable testing, it is already used for testing in metal-clad substations and is being recommended for CGI cable testing.

7.2 General Description of Test Method

The test circuit consists basically of a dc voltage supply which charges a capacitance C_1 , and a cable capacitance C_2 . After the test voltage has been reached, the capacitance is discharged over an air coil with a low inductance. This causes an oscillating voltage in the kHz range. The choice of C_1 and L depends on the value of C_2 to obtain a frequency between 1 and 10 kHz.

7.3 Advantages

- ◆ The OW method is based on an intrinsic ac mechanism.
- ◆ The principal disadvantages of dc (field distribution, space charge) do not occur.
- ◆ The method is easy to apply.
- ◆ The method is relatively inexpensive.

7.4 Disadvantages

- ◆ The effectiveness of the OSW test method in detecting defects is better than with dc but worse when compared with ac (60 Hz).
- ◆ In particular for medium voltage cable systems, the factor $f^* \text{ OSW} / 60 \text{ Hz}$ voltage is approaching 1, indicating the mutual equivalence.
- ◆ For HV cable systems $f^* \text{ OSW} / 60 \text{ Hz}$ is significantly higher (1.2 to 1.9) which means that OSW is less effective than 60 Hz.
- ◆ For both HV and MV cable systems, $f^* \text{ OSW} / \text{DC}$ is low (0.2 to 0.8) indicating the superiority of OSW over dc voltage testing.

{Note *: $f^* \text{ OSW} / 60 \text{ Hz}$ is the ratio of breakdown values for a dielectric containing a standard defect when using respectively OSW voltage and 60 Hz voltage.}

7.5 Test Apparatus

The cable is charged with a dc voltage and discharged through a sphere gap into an inductance of appropriate value so as to obtain the desired frequency. The voltage applied to the cable is expressed by:

$$V(t) = V_1 e^{-\alpha t} \sqrt{LC} \cos 2 \pi f t \quad (15.7)$$

where

V_1	=	charging voltage provided by the generator
α	=	damping ratio
C	=	$C_1 + C_2$

$$f = 1 / 2\pi \sqrt{LC}$$

Other test circuits are possible and give alternative solutions using different circuit configurations.

7.6 Test Procedure

Many tests carried out so far are of an experimental nature. Artificial defects like knife cuts, wrong positions of joints and holes in the insulation were created and subjected to different testing procedures of which one method was the OSW testing method.

These test procedures were intended to obtain breakdown as a criterion for comparison. The general testing procedure is as follows:

- Start to charge the cable with a dc voltage of about 1 or 2 times operating voltage.
- Increase with steps of 20 to 30 kV.
- Produce 50 shots at each voltage level.
- Time interval between shots 2 to 3 minutes.
- Proceed until breakdown occurs.

In one case, the Dutch testing specification for HV extruded cables, the OSW method is mentioned as a withstand test to be used as an after laying (installation) test. The test procedure is as follows:

- Charge the cable slowly, using the dc power supply.
- After reaching the value of $3 V_0$, the dc source will be disconnected and the rapid closer activated.
- The cable circuit will be discharged through a reactor, causing the OSW testing voltage.
- This procedure should be repeated 50 times.

In the Netherlands the OSW testing method is applied several times as an after laying test for HV extruded cable systems.

7.7 Further Development Work

Since the effectiveness of the OSW testing method is not as high as would be desired, it might be very attractive to combine OSW with partial discharge (PD) site detection as an additional source of information. In the literature, details are given of an automatic PD measurement system, enabling statistical analysis and generating phase, time and amplitude resolved PD finger prints. Compared to ac 50/60 Hz generated PD finger prints, additional information results from the decreasing voltage amplitude of each OSW pulse. For medium voltage cable systems according to [14-8], this measuring system looks feasible.

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